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THEORETICAL VERSUS EXPERIMENTAL RESULTS FOR AIR BLAST FROM ONE-POUND SPHERICAL TNT AND PENTOLITE CHARGES AT SEA LEVEL CONDITIONS

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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THEORETICAL VERSUS EXPERIMENTAL RESULTS FOR AIR BLAST FROM ONE-POUND SPHERICAL TNT AND PENTOLITE CHARGES AT SEA LEVEL CONDITIONS

Prepared by:
M. Lutzky

ABSTRACT: Numerical computations, using a one-dimensional hydrodynamic code on an IBM 7090, have been made for the detonation of 1-lb spheres of pentolite and TNT at sea level. Positive durations, overpressure at the main shock, and space-time paths of the main shock, second shock, and contact surface are compared with experimental data. It is found that the calculated peak pressures at the main shock are 10 per cent too low, the experimental second shock path lies about 40 per cent above the calculated one, and the experimental contact surface path is about a factor of two greater in radius than the calculated one. Possible explanations for these deviations are discussed.

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THEORETICAL VERSUS EXPERIMENTAL RESULTS FOR AIR BLAST FROM ONE-POUND SPHERICAL TNT AND PENTOLITE CHARGES AT SEA LEVEL CONDITIONS

The numerical calculation, by means of computer codes, of the effects of a chemical explosion in air is an important tool for the investigation of the efficient utilization of high explosives for blast damage. In addition, much information can be gained about the behavior of the explosives themselves, both during and after detonation, by comparing the results of such computations with experiment. Calculations for 1-lb spheres of TNT and pentolite detonated in air at sea level are reported, and compared with experimental results. An attempt is made to connect the discrepancies found with possible deficiencies in the model used to describe the detonation of a chemical explosive.

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This report has been approved for open publication by the Department of Defense, Office of Assistant Secretary of Defense (Public Affairs).

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By direction

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INTRODUCTION

One of the most important methods available for the theoretical prediction of blast effects in air is the solution of the hydrodynamic equations by finite difference methods using an electronic computer. The present investigation is concerned with the blast wave and other phenomena arising from the detonation of small spherical charges at sea level and their computation by numerical methods. In particular, we present results for the detonation of 1-lb spheres of pentolite and TNT at sea level and we compare these results with available experimental data.

THE NUMERICAL COMPUTATIONS

The hydrodynamic code used in these computations utilizes the Von Neumann-Richtmyer artificial-viscosity technique,[1] and is fully described elsewhere.[2] The basic idea is to solve a set of finite difference equations (which approximate the partial differential equations of gas dynamics) by a step-by-step procedure advancing in time. The physical situation is assumed to be spherically symmetric, so that all quantities are functions only of the radius and the time; the origin of coordinates is chosen to be at the center of the explosive. Hydrodynamic variables are assigned values in a set of spatial zones covering the range of interest at time $t = 0$, and the flow evolves from these initial conditions. The origin of time is taken at the instant the detonation wave reaches the surface of the explosive, so that the solid explosive has been completely converted to gaseous detonation products.

The equation of state used for the detonation products is the LSZK equation,[3] and the initial conditions in the detonation products are represented by a spherical Taylor wave.[3,4] The equation of state for the air is $E = P/\rho(\gamma-1)$, where γ is a fit by straight line segments[2] to the tables of Hilsenrath and Klein,[5] and is taken to be a function of internal energy, E, and density, ρ. The parameter γ is not equal to the ratio of specific heats, except in the low-energy domain.

Since the artificial-viscosity mechanism has the tendency to smooth out shock fronts so that they extend over a small number of spatial zones, it is necessary to define how values are to be read at a shock. The position of the shock is located in the numerical results as the point at which the artificial viscosity is a maximum, and the pressure is taken to be the pressure at the first maximum (in pressure) immediately behind this point.

THE EQUATION OF STATE FOR DETONATION PRODUCTS

We have chosen to describe the detonation products by the LSZK (Landau, Stanyukovich, Zeldovich, and Kompaneets) equation of state, which treats the products by drawing an analogy between the state of the detonation products of a condensed explosive and the crystal lattice of the solid state. Details concerning the derivation and significance of the LSZK equation of state are given elsewhere,[3] and we present here only a brief summary of the relevant equations and values for the various constants. The (E, P, ρ) form of the LSZK equation may be written:

$$P = \frac{E\rho}{\alpha} + B\rho^{\gamma}\left\{1 - \frac{1}{\alpha(\gamma-1)}\right\}, \tag{1}$$

where P = pressure, ρ = density, E = internal energy/unit mass, α and γ are dimensionless constants, and B is a constant with dimensions $(ML^{-3})^{1-\gamma}$ (L^2T^{-2}). The three undetermined constants, α, γ, and B, must be evaluated by using experimental results. It is sufficient to know the detonation velocity versus loading density relationship and the value of the heat of detonation for the solid explosive, if, in addition, we postulate that the detonation gases approach ideal gas behavior at small densities. The procedure for evaluating the constants has been described elsewhere[3] for TNT, and the results are:

$$\begin{aligned} \alpha &= 2.9412 \\ \frac{B}{Q} &= 0.53562 \left(\frac{gm}{cm^3}\right)^{1-\gamma} \\ \gamma &= 2.78, \end{aligned} \tag{2}$$

where Q = 1018 calories/gram = heat of detonation, and the ideal gas value for the ratio of specific heats of the products at low densities was taken to be $\gamma_i = 1.34$. Using these values, the spherical Taylor Wave for TNT at a loading density of ρ_0 = 1.625 gm/cc was calculated and used for the initial condition for the products at $t = 0$. Equation (1), with the values of the constants given in (2), is then used for the subsequent calculation of the state of the detonation products for $t > 0$.

Precisely the same procedure is applicable to pentolite, and has been carried out to yield the following results:

$$\alpha = 2.9412$$

$$\frac{B}{Q} = 0.53927 \left(\frac{gm}{cm^3}\right)^{1-\gamma}$$

$$\gamma = 2.64,$$

where Q = 1260 cal/gm was used for the heat of detonation, and the experimental curve for detonation velocity versus loading density was taken from Cook.[8] The value of γ_1 used was 1.34 as for TNT. The initial density of the solid explosive was taken to be ρ_0 = 1.67 gm/cc.

COMPARISON WITH EXPERIMENTAL DATA FOR PENTOLITE

A comprehensive compilation and analysis of free-air blast data from pentolite detonations has been produced by Goodman,[7] the results of which will be used in this report to provide comparisons with the theoretical pentolite calculations. The quantities we shall consider for pentolite are the overpressure-distance curve for the main shock, the radius-time path of the main shock, and the positive duration as a function of distance. Goodman has reported these quantities as single curves, which are obtained by averaging and smoothing the results of many different experimental determinations. Since neither ambient pressures nor temperatures were usually reported, all measurements were arbitrarily assumed to have been made at 14.7 psi and 300°K with ambient sound speed 1139.4 ft/sec. The charge density was assumed to be 1.65 gm/cc, which is close to the value used in the theoretical calculation of ρ_0 = 1.67 gm/cc.

Figure 1 is a plot of shock overpressure (total pressure minus ambient pressure) versus radial distance. The dashed curve represents the smoothed numerical fit of Goodman to the experimental data, while the solid curve represents the calculated result. In the range 0.2 - 1.5 feet, the behavior of the calculated curve is characterized by the phenomenon of shock formation, consisting of a sharp rise in pressure at early times, followed by an overshoot region in which the calculated curve lies 10-20 per cent above the experimental curve. The region is probably dominated by purely computational effects which have little to do with the actual physical phenomena. Thus, in a real gas, the shock formation is governed by viscous and heat conduction effects; however, in numerical calculations of this type the analogous quantity is an artificial viscosity which is quadratic in the space gradient of the particle velocity, rather than linear, as is a real viscosity. The artificial viscosity is constructed to yield the correct entropy across a shock but does not reproduce the proper shape or extent of the shock transition itself, nor does it reproduce properly the physical phenomenon of shock formation. Furthermore, some difficulty arises at the interface between the gas products and the air, due to the fact that the zones on either side of the interface have widely different masses.[8] It would therefore seem unwise to ascribe too much physical significance to the early stages of the calculation.

At approximately 1.5 feet the calculated curve crosses the experimental one; and from then on the two curves remain parallel, the calculated values lying about 10 per cent below the experimental values. The reason for this discrepancy is not yet clear. Various possible explanations will be discussed in a subsequent section of this report.

Figure 2 is a radius-time plot of various aspects of interest in the flow. The upper two curves depict the arrival times for the main shock;

the solid curve represents the calculated arrival times, and the dashed curve represents a smoothed, numerical fit to the experimental data.[7] Also shown is the calculated radius-time plot for the contact surface separating the detonation products from the shocked air. Each of the successive relative minima in this curve represents a point at which an internal shock in the detonation products passes into the air, at the same time reflecting another shock inward toward the center. The first of these subsidiary shocks will be considered in detail for TNT, in the next section, as experimental data exist for the location of this shock for this explosive.

The remaining curve is useful in calculating positive durations, and represents the path of that point behind the main shock at which the pressure is equal to the ambient air pressure (overpressure equals zero). A slight dip is discernible in this curve at about 120 μsecs, and is due to the fact that at this time the second shock*(the shock coming back through the detonation gases) crosses the zero overpressure curve. It is clear from this curve that the point of zero overpressure remains within the explosion products until 800 μsecs, at which time it emerges into the compressed air behind the main shock. At this point a change in the slope of the zero-overpressure curve occurs. This results in a discontinuity in the slope of the positive duration versus time curve depicted in Figure 3.

The solid curve of Figure 3 is the calculated one, and the dashed curve is a smoothed numerical fit to Goodman's compiled pentolite data. The cusp does not appear in the experimental curve, although the general trend of the two curves appears to be the same. The absence of the cusp in the experimental data might be explained by the sparsity of experimental points in that particular region,**and/or by the fact that the dashed curve is a smoothed numerical fit to experimental data which display a fair amount of scatter.

In any case, the agreement shown in Figure 3 is considered to be fairly good in view of the fact that the positive duration depends on the conditions in the whole field at successive times, and is therefore subject to many sources of perturbation and error.

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* This shock originates at the interface between the detonation gases and the air. It moves inward into the detonation gases, is reflected from the center, and then proceeds outward, emerging from the detonation products at about 1750 microseconds.

**Recent pressure measurements, on a large hemispherical charge constructed from 32-lb blocks of TNT, have been made in this region. The results indicate that the cusp does exist for this multiton explosion. We are indebted to Mr. John Keefer of the Ballistics Research Laboratories for this unpublished information. In addition, Adushkin and Korotkov[15] have experimentally detected a cusp in the positive duration curve, although they ascribe this effect to late shock formation.

COMPARISON WITH EXPERIMENTAL DATA FOR TNT

A comprehensive analysis of experimental data for TNT, along the lines of the Goodman report on pentolite, does not exist at present, so that we content ourselves with data from particular TNT experiments. We shall make use of experimental data from the work of Fisher[9,10] (first and second shocks), Weibull[11] (first shock), Potter and Jarvis[12] (first and second shocks), and Rudlin[13,14] (first and second shocks, and contact surface*). It should be noted that the loading densities were not the same for all of these experiments. Fisher used ρ_0 = 1.51 gm/cc, Rudlin used various densities ranging from ρ_0 = 1.01 gm/cc to ρ_0 = 1.625 gm/cc, and the densities used by Potter and Jarvis were not available. The loading density used for the theoretical calculation was ρ_0 = 1.625 gm/cc. The calculated quantities for TNT which we shall compare with experiment are the overpressure-distance curve for the main shock, and the radius-time paths of the main shock, second shock, and contact surface.

Figure 4 presents a plot of the calculated overpressure-distance curve for TNT as a solid curve. Individual points are plotted for the experimental data. (Two types of data reduction were done by Fisher in order to obtain the peak pressures: pressures were obtained from velocity-line data, and also from pressure-time records. Both types of measurements are recorded in Figure 4.)

The general behavior is similar to that of the previous pentolite curves; that is, beyond a certain point the calculated overpressure-distance curve remains fairly consistently about 10 per cent below the experimental values.

Figure 5 is a radius-time plot for TNT, presenting as solid curves the calculated paths of the main shock, the second shock (after it has emerged from the detonation products) and the contact surface. The general trend of the experimental data for the main shock suggests a behavior similar to that of pentolite; that is, at early times the experimental points lie below the theoretical, crossing over eventually and remaining slightly above the calculated curve.

A new feature of these curves, not available for the pentolite results, is the capability of comparing with experiment the space-time paths for the second shock and for the contact surface. Figure 5 shows that the experimental second shock path lies about 40 per cent above the calculated one, while the experimental contact surface path is about a factor of two greater in radius than the calculated one. These are serious deviations, of a much greater magnitude than the discrepancies in the behavior of the main shock, and their removal may require some fundamental changes in the calculation and in the model used.

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* Since Rudlin's measurements of the contact surface are unpublished, we mention here that they are photographic observations of the luminous front, made on high-speed Ektachrome color film.

DISCUSSION

Several possibilities can be considered in an attempt to explain the various discrepancies noted between the experimental and theoretical results. One which is easily disposed of involves the difference between the loading densities used for the experiments and for the theoretical calculation. Various experimenters used densities ranging from ρ_0 = 1.51 - 1.625 gm/cc for TNT, while the theoretical calculation used ρ_0 = 1.625 gm/cc. A numerical calculation for ρ_0 = 1.57 gm/cc showed essentially no difference with the ρ_0 = 1.625 gm/cc calculation. Furthermore, examination of the experimental points on Figures 4 and 5 fails to disclose any dependence on initial density, so that it is probably safe to discount this particular explanation.

It may also be argued that a change in the equation of state of the detonation products may relieve the situation somewhat. To test the effect of such a change, a calculation has been carried out in which the LSZK equation of state has been replaced by an ideal gas equation of state, while the total energy of the explosive (in this case, a 1-lb sphere of pentolite) is kept constant. The results are presented in Figure 6, where the solid curve represents the LSZK calculation, and the dashed curve represents the ideal gas calculation.

The ideal gas calculation results in a main shock which is essentially coincident with the LSZK main shock, and a second shock whose path lies about 10 per cent above the path of the LSZK second shock. Because of the fact that the second shock leaves the detonation products earlier in the ideal gas calculation, the path of the contact surface for later times is shifted to the left. However, the maximum radius attained by the contact surface remains unchanged, as does its final asymptotic position. From this single numerical experiment we can thus draw the tentative conclusion that the main shock behavior and the maximum radius attained by the contact surface depend only on the initial energy of the explosion. The second shock position, however, does depend on the equation of state chosen for the detonation products. Nevertheless, although it does seem possible to affect the second shock behavior by manipulating the equation of state of the detonation products, it would probably require quite a radical revision to achieve the corrections necessary to match experimental results. Furthermore, as long as the total energy of the explosion remains the same, it is doubtful if the discrepancies in the main shock and contact surface can be removed by this procedure. Since there exists some disagreement on precise values for the heats of detonation of explosives, one might try to correct the main shock behavior by increasing the heat of detonation by a suitable amount in the theoretical calculation. This does result in a suitably adjusted main shock (at least in the region where the main shock pressures were initially too low) but shifts the position of the contact surface and second shock by approximately the same percentage as the main shock, which is hardly enough to account for the discrepancies.

Perhaps a reasonable approach is to combine the last two ideas by adjusting the heat of detonation to give the correct main shock behavior, and to try to find a suitable equation of state for the detonation products which will remove the remaining discrepancies in the second shock and contact surface. On the other hand, the realization that the second shock behavior is affected strongly by the state of the detonation products leads one to remember that the theoretical calculation is a highly idealized one which omits consideration of many phenomena. In particular, the numerical calculation does not take into account possible reaction-zone effects, turbulence, jetting, incomplete combustion, mixing, afterburning, etc. It is quite conceivable that some or all of these effects are important and that a more accurate prediction can be obtained only when a more sophisticated model is postulated for the behavior of the expanding gases. More detailed experimental determination of the explosion phenomena may be required for the creation of a satisfactory theoretical model.

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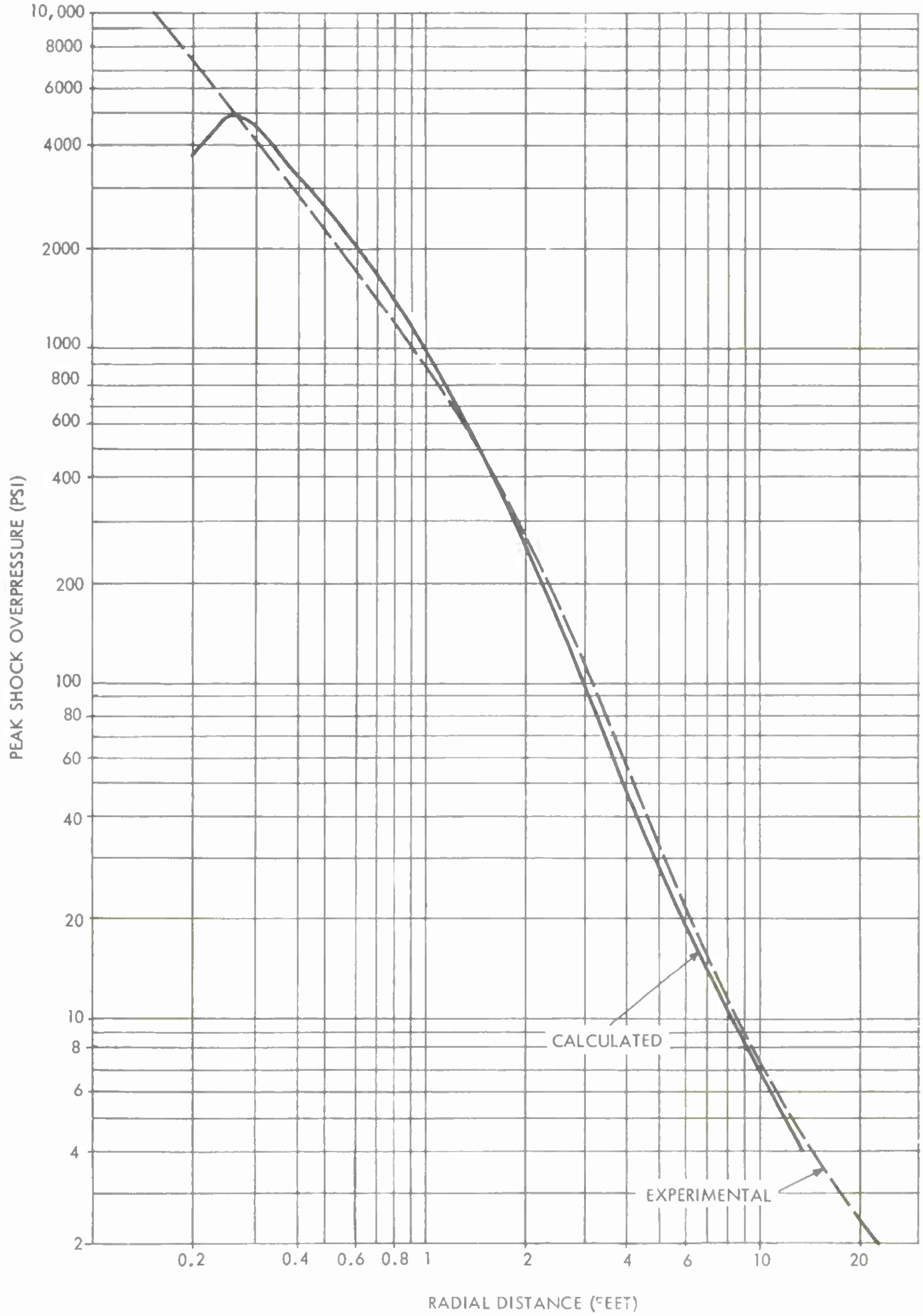

FIG. 1 PEAK SHOCK OVERPRESSURE VS. RADIAL DISTANCE, 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

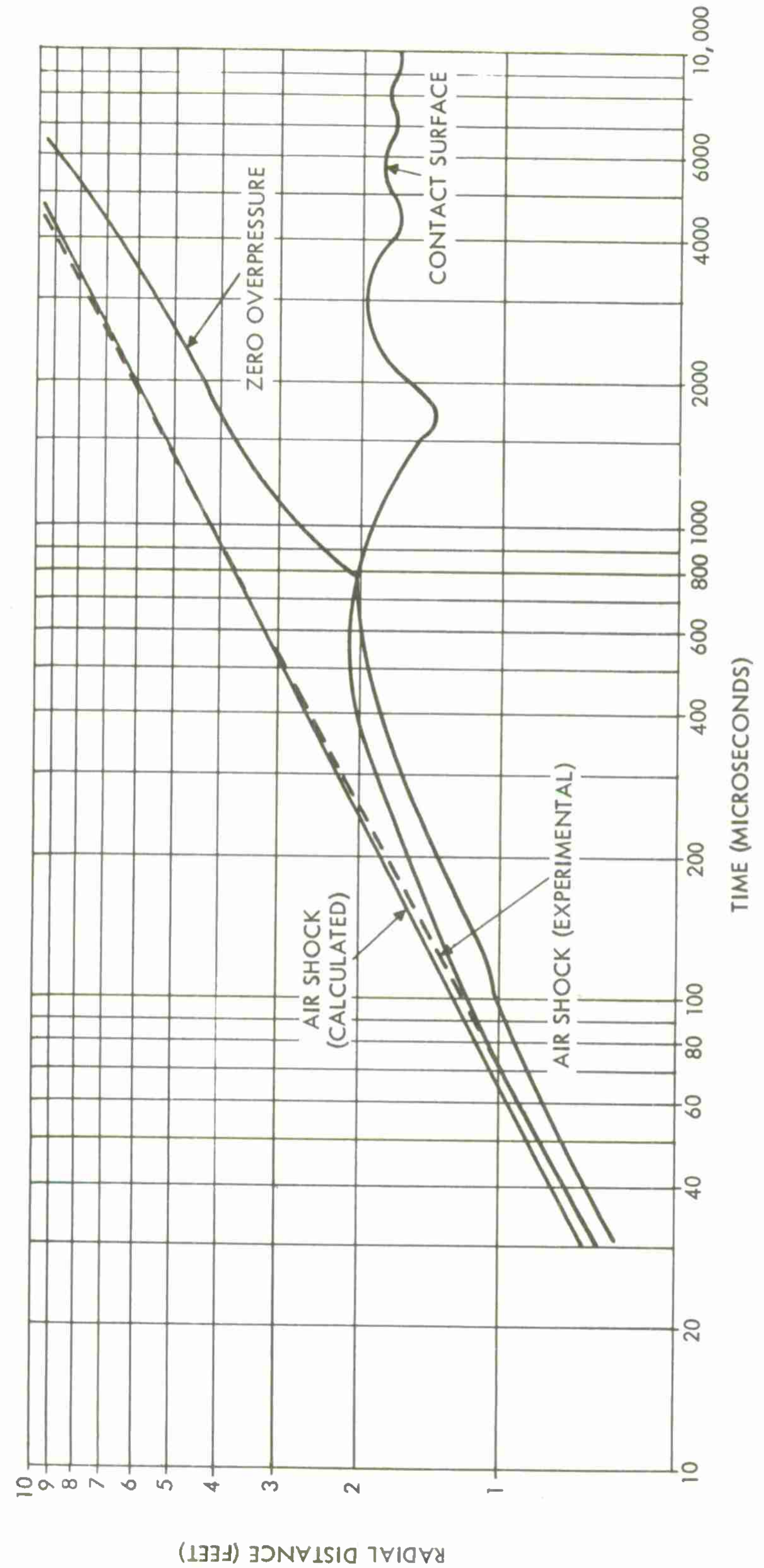

FIG. 2 RADIUS-TIME CURVES FOR 1-LB SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

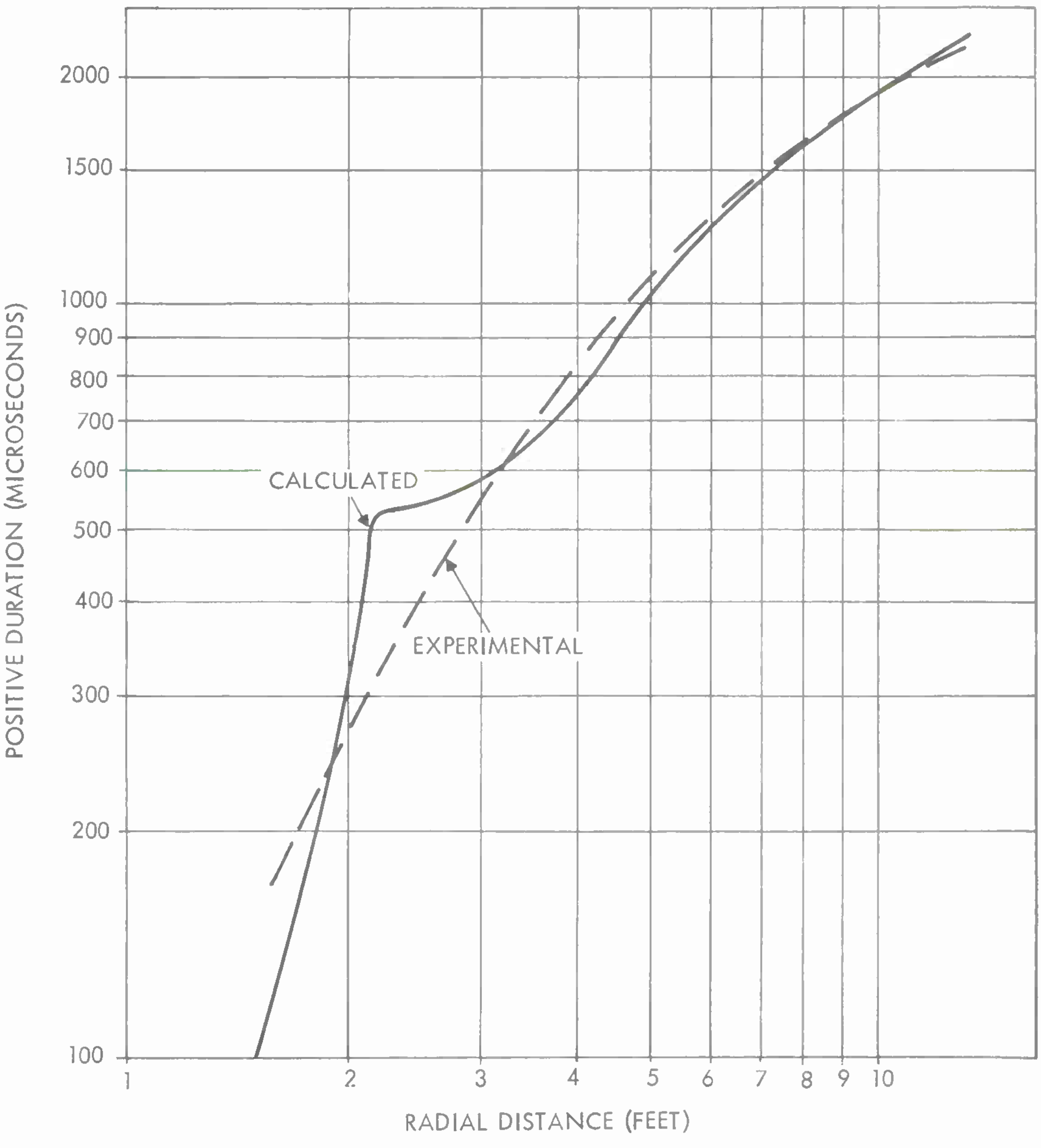

FIG. 3 POSITIVE DURATION VS. RADIAL DISTANCE, 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

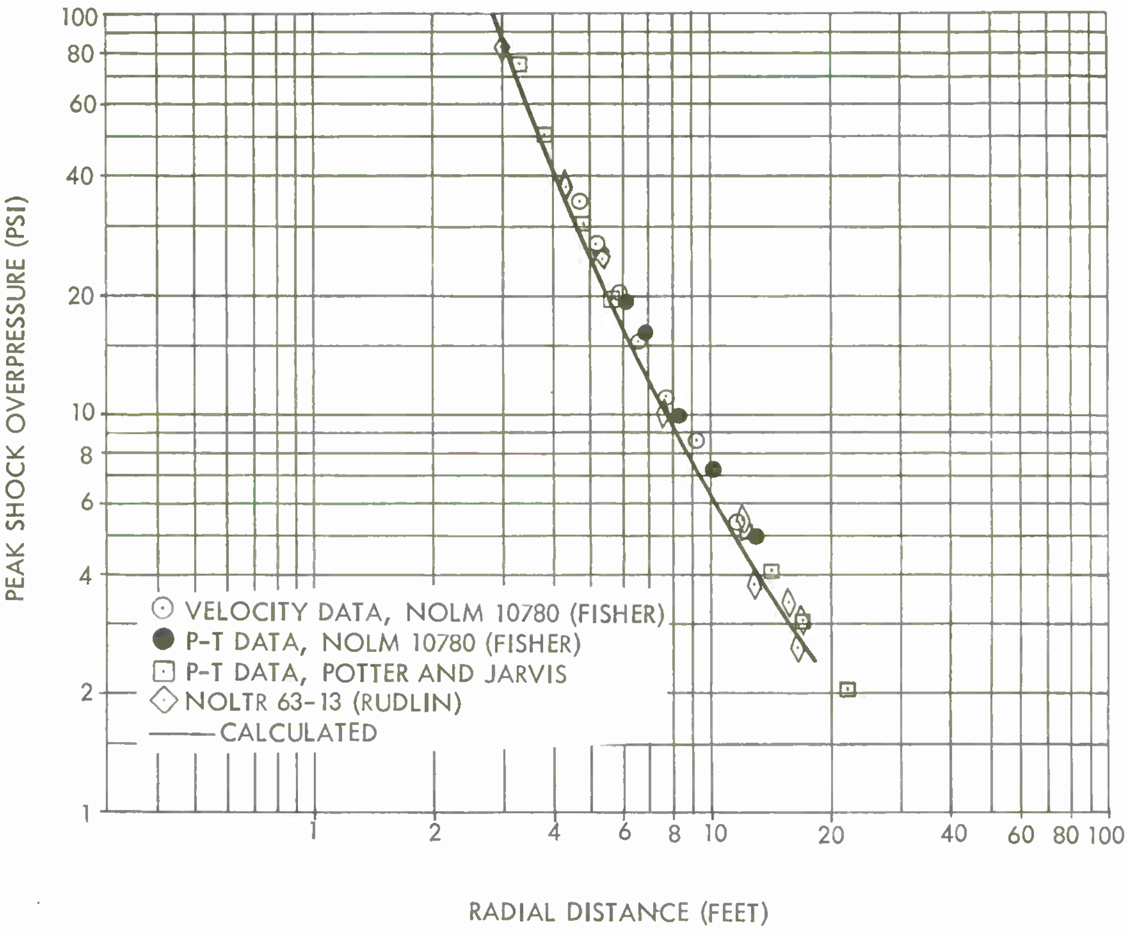

FIG. 4 PEAK SHOCK OVERPRESSURE VS. RADIAL DISTANCE, 1-LB. SPHERE OF TNT AT SEA LEVEL CONDITIONS

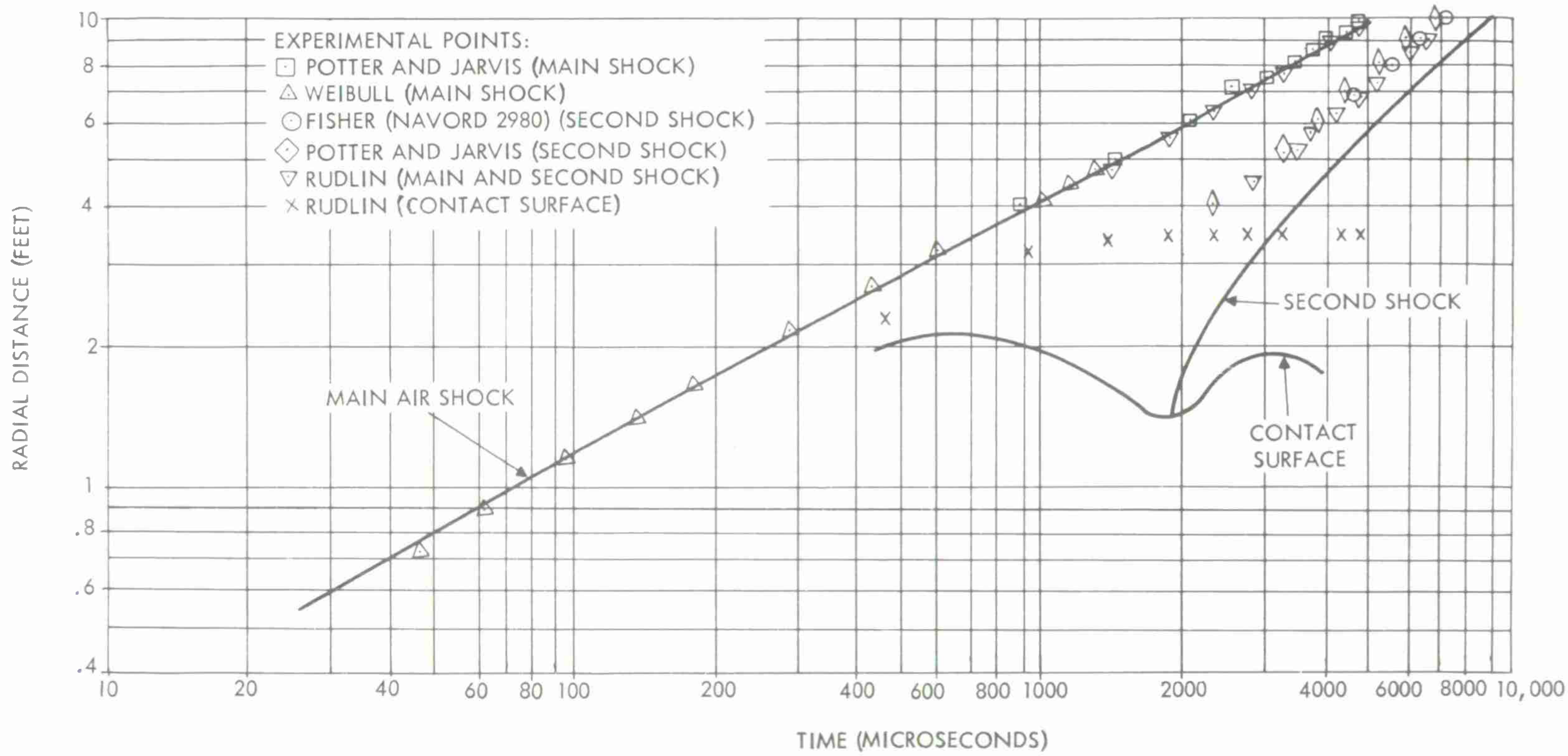

FIG. 5 RADIUS-TIME CURVES FOR 1-LB. SPHERE OF TNT AT SEA LEVEL CONDITIONS

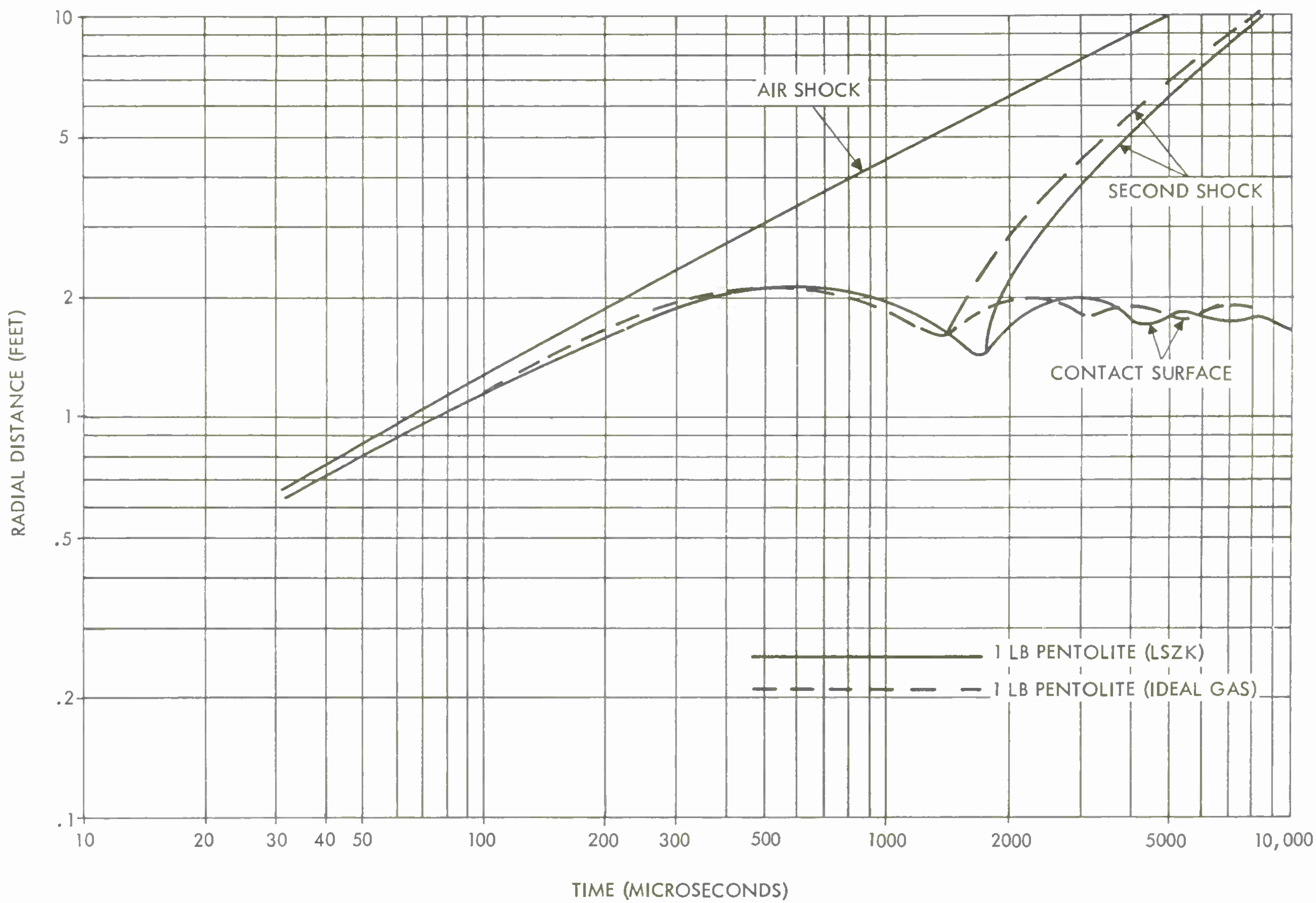

FIG. 6 RADIUS-TIME CURVES FOR 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS, FOR IDEAL GAS AND LSZK EQUATIONS OF STATE

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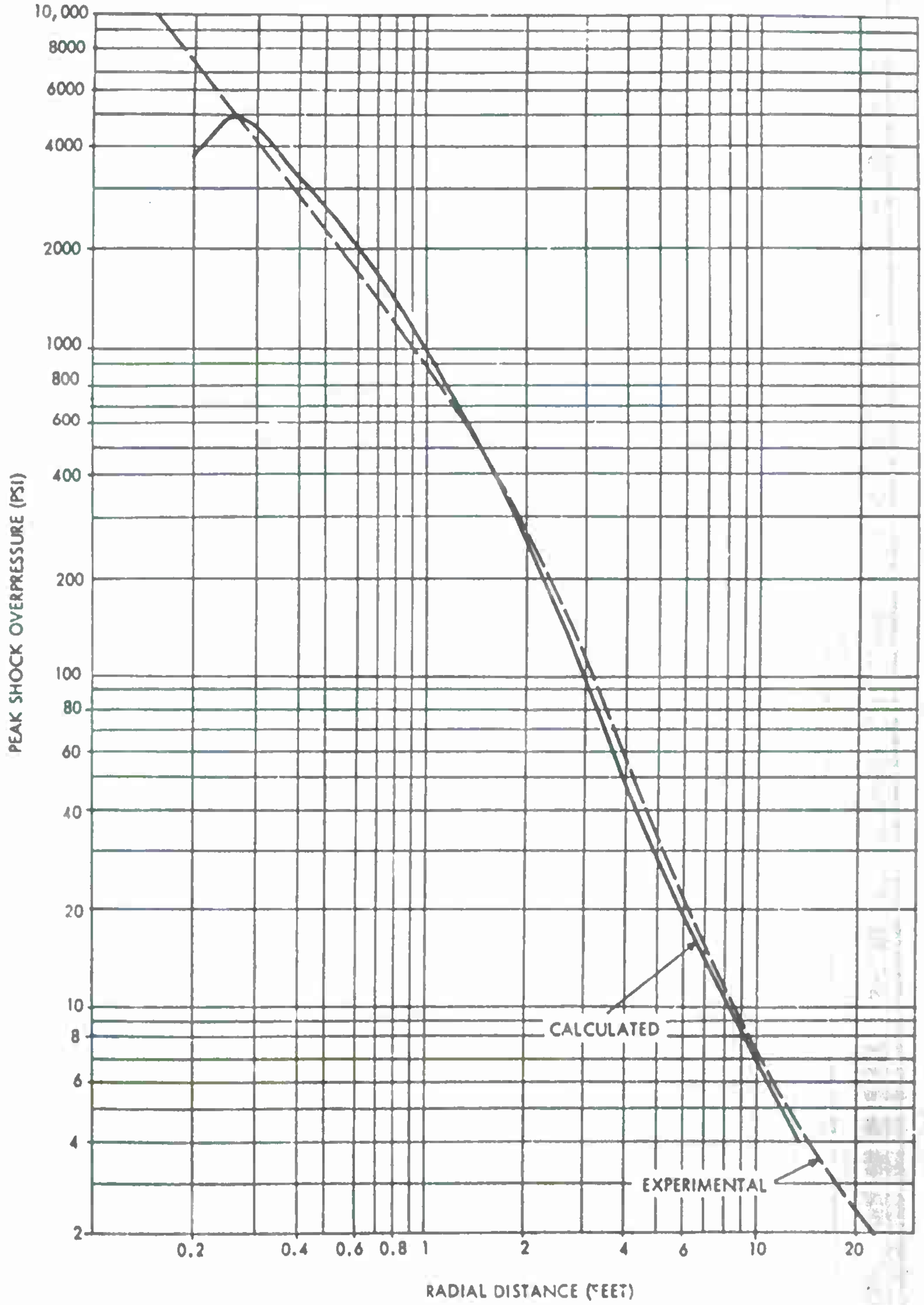

FIG. 1 PEAK SHOCK OVERPRESSURE VS. RADIAL DISTANCE, 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

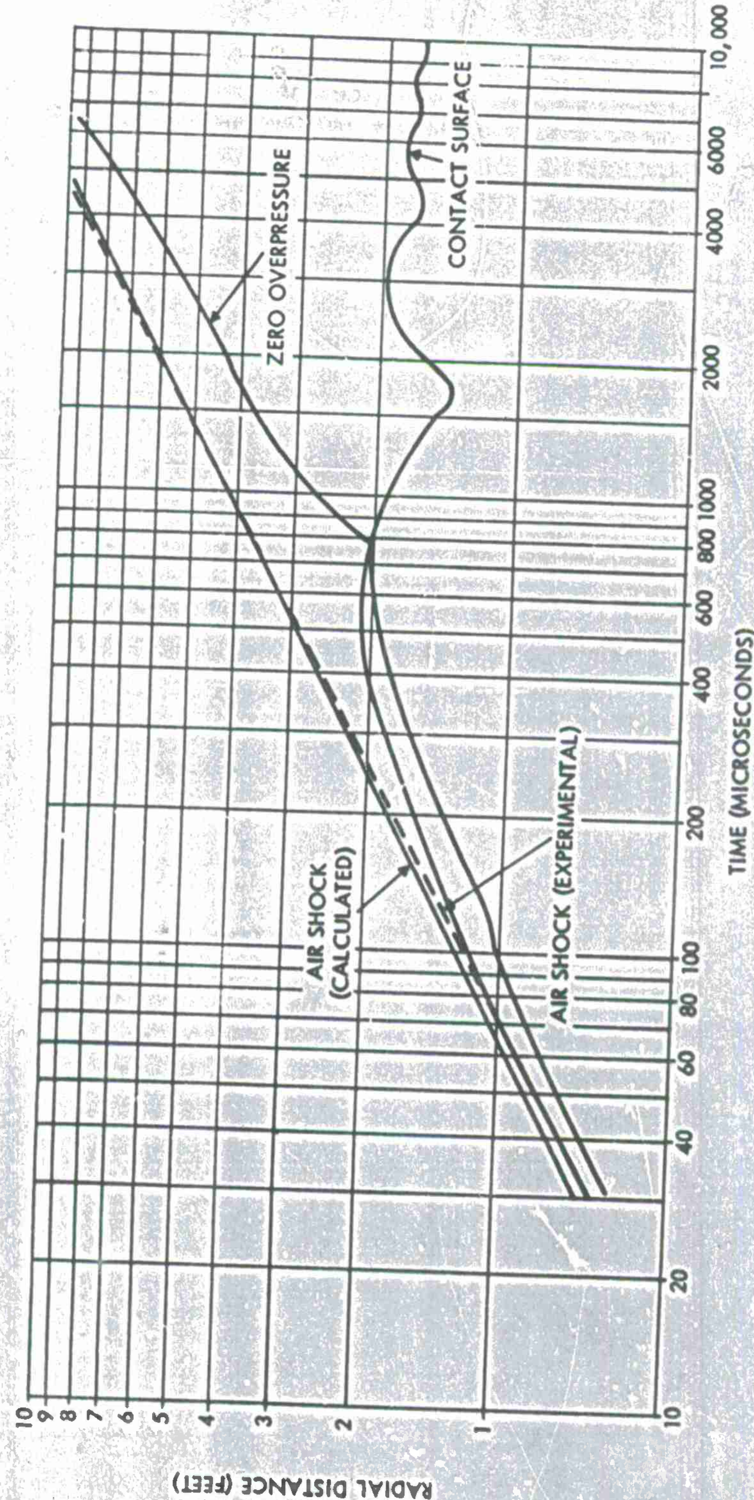

FIG. 2 RADIUS-TIME CURVES FOR 1-LB SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

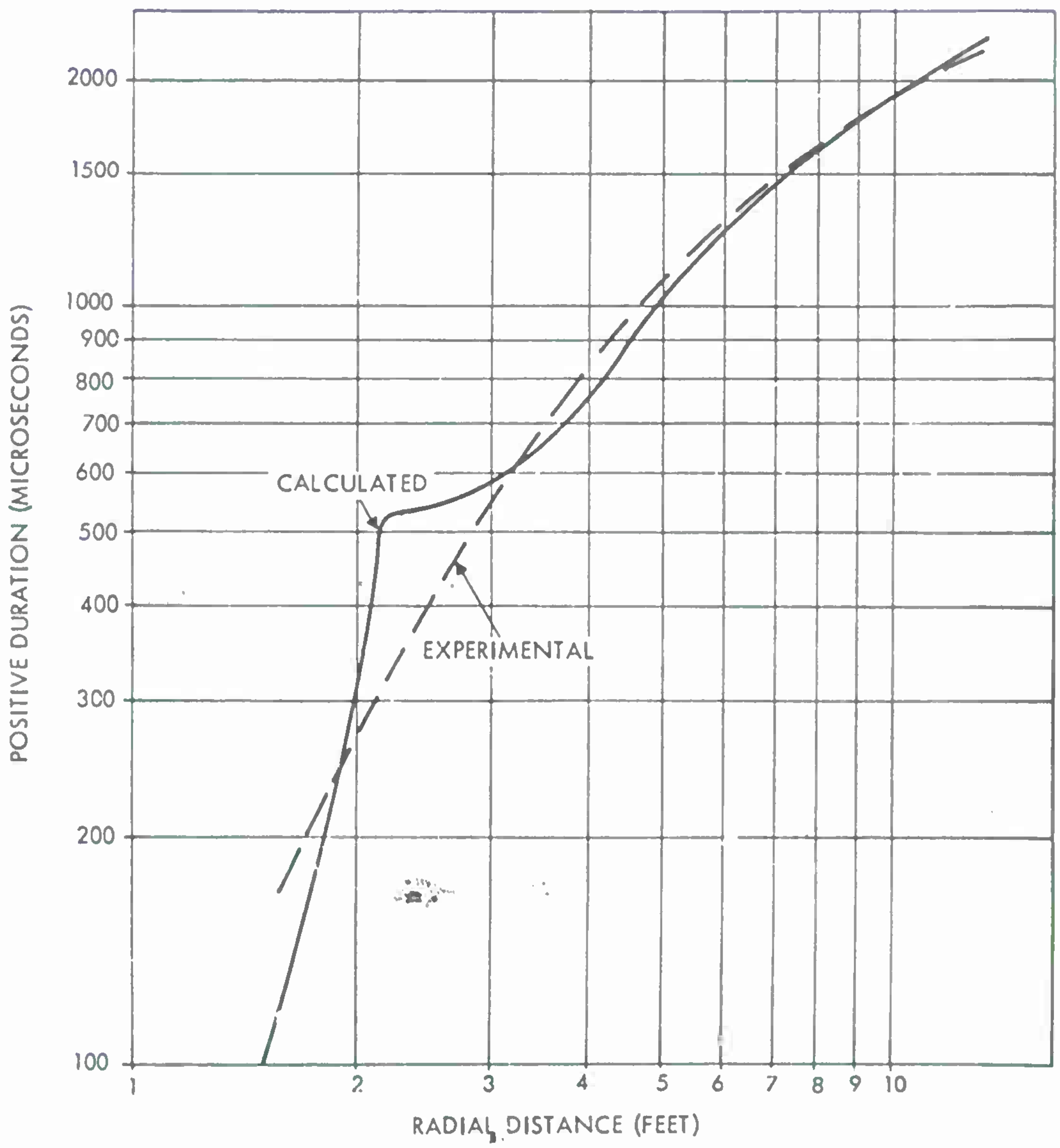

FIG. 3 POSITIVE DURATION VS. RADIAL DISTANCE, 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS

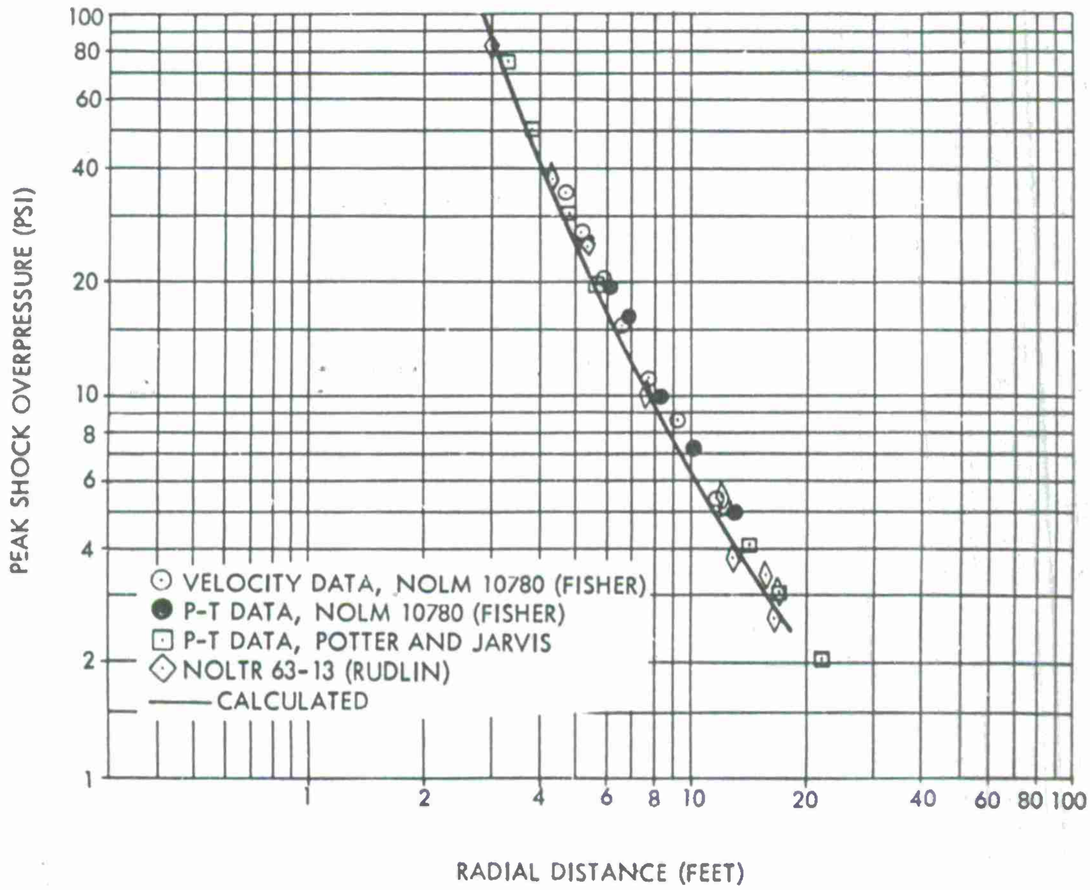

FIG. 4 PEAK SHOCK OVERPRESSURE VS. RADIAL DISTANCE, 1-LB. SPHERE OF TNT AT SEA LEVEL CONDITIONS

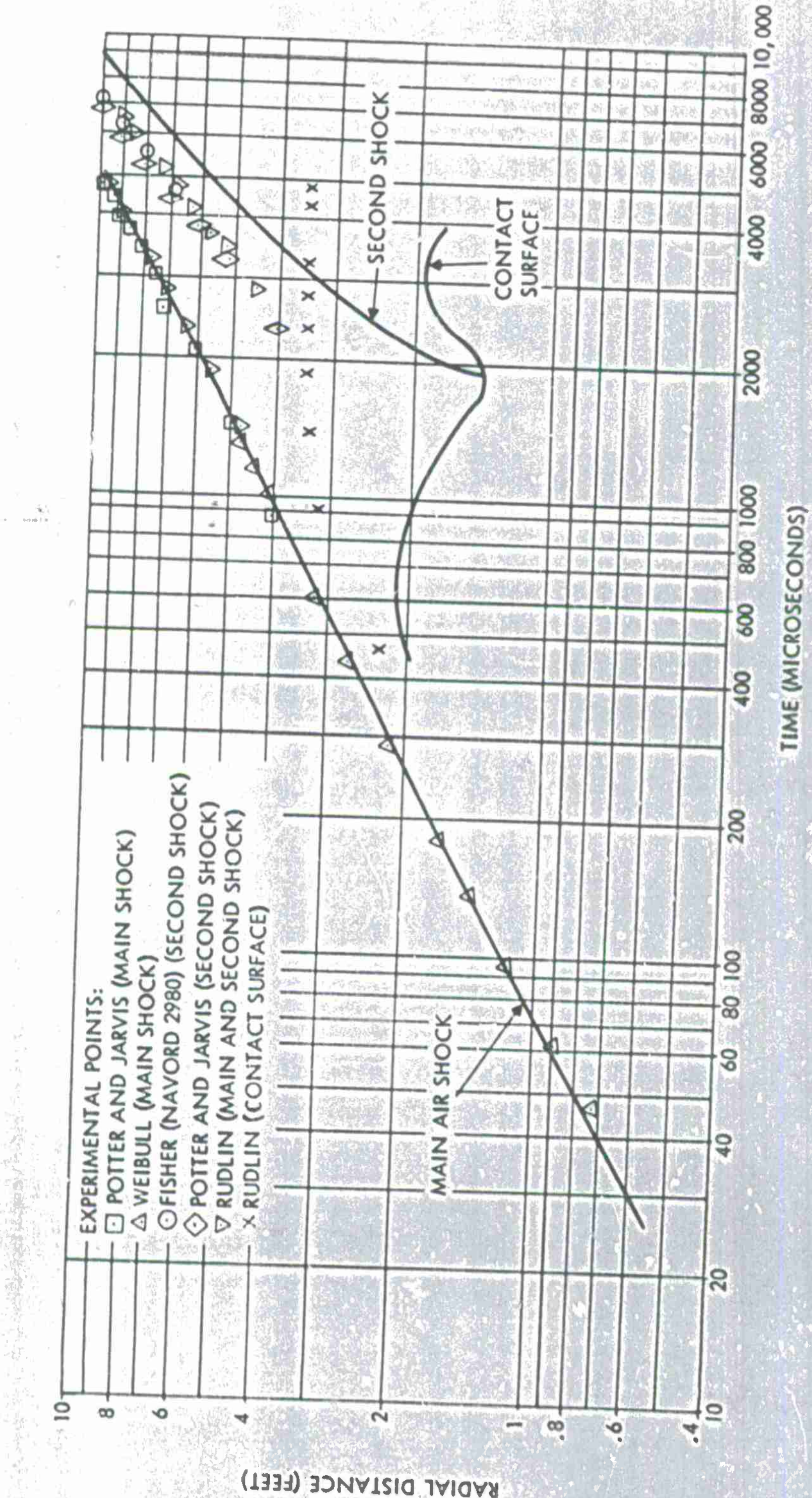

FIG. 5 RADIUS-TIME CURVES FOR 1-LB. SPHERE OF TNT AT SEA LEVEL CONDITIONS

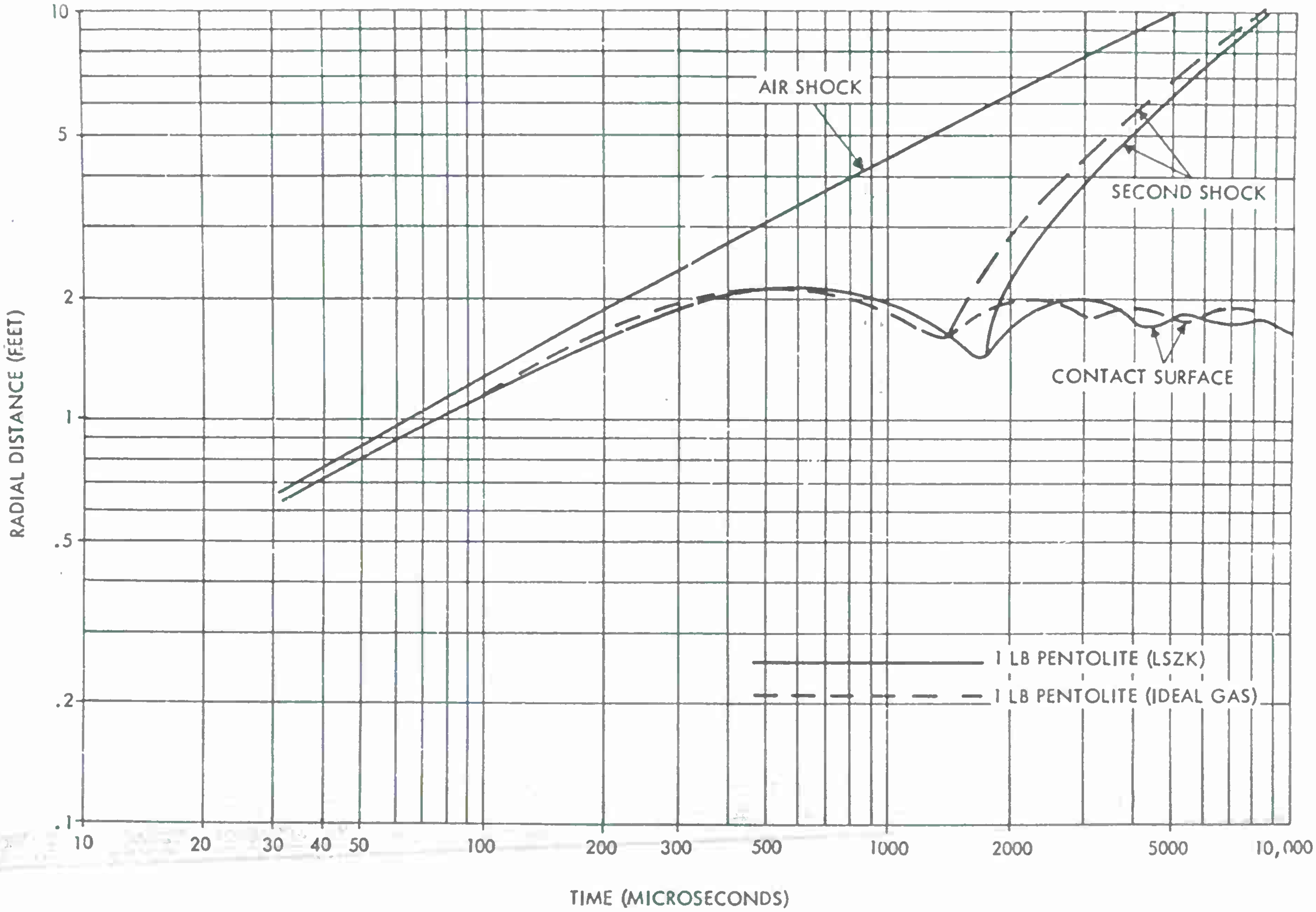

FIG. 6 RADIUS-TIME CURVES FOR 1-LB. SPHERE OF PENTOLITE AT SEA LEVEL CONDITIONS, FOR IDEAL GAS AND LSZK EQUATIONS OF STATE

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Numerical computations, using a one-dimensional hydrodynamic code on an IBM 7090, have been made for the detonation of 1-lb spheres of pentolite and TNT at sea level. Positive durations, overpressure at the main shock, and space-time paths of the main shock, second shock, and contact surface are compared with experimental data. It is found that the calculated peak pressures at the main shock are 10 per cent too low, the experimental second shock path lies about 40 per cent above the calculated one, and the experimental contact surface path is about a factor of two greater in radius than the calculated one. Possible explanations for these deviations are discussed.

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